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AN IMPROVED MODEL FOR FLUID-DRIVEN CRACKS IN JOINTED ROCK

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An improved model for fluid-driven cracks in jointed rock

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ABSTRACT

The finite element model FEFFLAP (Finite Element Fracture and Flow Analysis Program) is being developed for and applied to hydrofracture analyses in support of the Unconventional Gas Recovery Program at the Lawrence Livermore National Laboratory [1]. The major characteristics of FEFFLAP were presented earlier [2]. Two improvements made to the model are presented here: a multiple load capability and a selection of minimum aperture for fluid flow. The results of two verification and example problems are also given.

INTRODUCTION

FEFFLAP is a two-dimensional finite element program with linear solid elements and nonlinear joint elements. The solids part, which can simulate out-of-plane fracture propagation, is coupled with a flow program that uses current structural displacements to obtain flow rates and pressure in cracks and joints. The mechanics of the solid-fluid flow interaction are as follows: the fluid pressures produce boundary conditions that are used to elastically determine the apertures of the joints and cracks. The apertures are then used in the fluid flow model to determine flow rates and pressures. This process is repeated until convergence occurs. The non-linear behavior of joints is also iterated upon until convergence, within the flow interation loop. Joint elements are described by normal and shear stiffnesses, tensile strength, cohesion, friction angle, and maximum allowable closure.

The code is highly graphics oriented. Its operation is predominantly interactive on the computer. Rezoning for crack extension is done automatically. Crack instability and angle of propagation are determined from a user selected choice of three possible fracture criteria. Stress intensity factors are obtained from special crack tip finite elements that respond to the square root singularity in stresses at the crack tips.

Model development is being pursued actively, and significant enhancements have been implemented since the last report.

IMPROVEMENTS IN THE CODE

Multiple Load Capability

Analysis of fracturing processes involves the determination of the stress magnitude required to cause fracture initiation at a point or fracture instability at a crack tip. When a single load set is used, it is trivial to find the necessary load to cause fracture initiation or instability; the existing load is simply proportioned up or down according to material strength or fracture toughness. Typical physical processes usually involve more than one type of loading. An example is an underground hydraulically induced fracture. When multiple load sets are used, the determination of the necessary fracturing stress level is quite complicated. This general case can be clarified with the aid of Figure 1.

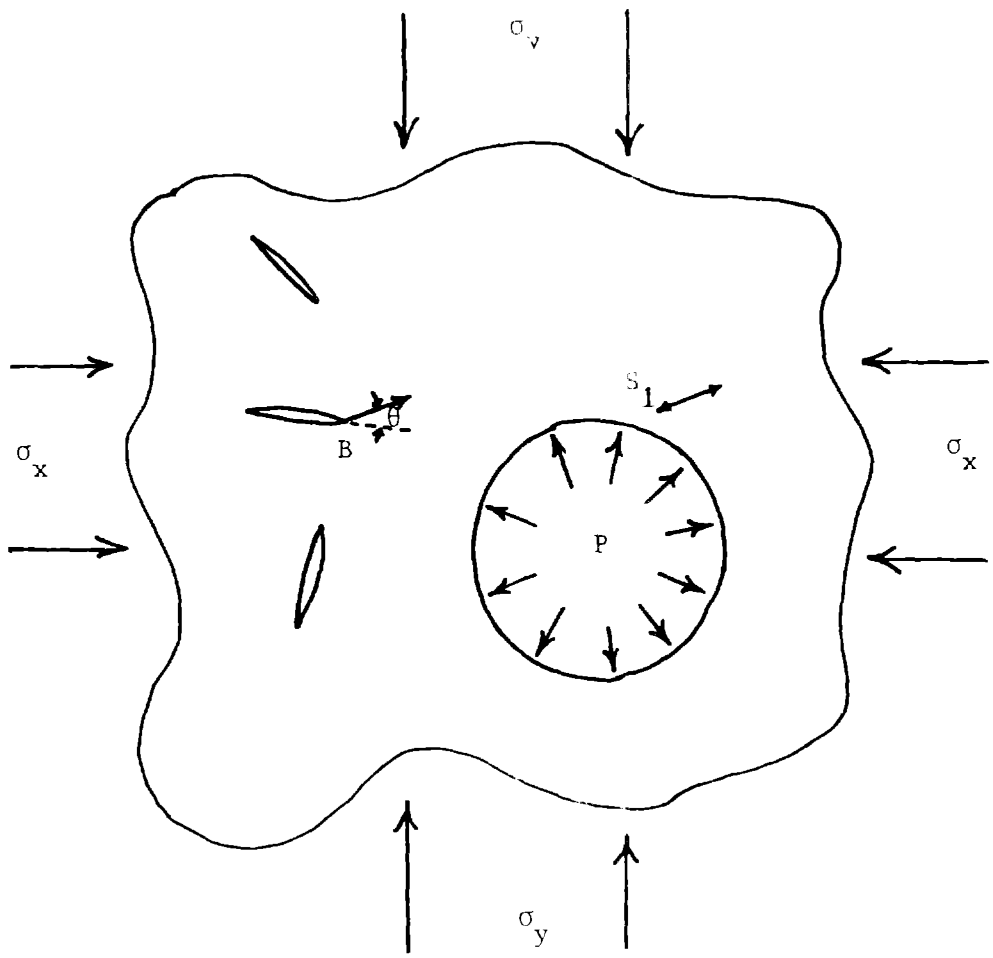

Figure 1: An Example of a Multiple Load Problem.

The field stresses at infinity σ_x and σ_y in Figure 1 are constant; note, however, that they can generate a non-uniform stress field inside the domain. The pressure in the borehole, P, has to be determined so that a crack will initiate, or an existing crack will propagate. Starting with an initial value of $P = P_o$, a stress analysis indicates that the maximum tensile principal stress is at the location and orientation shown as S_1. In addition, crack tip B has the highest stress intensity factors and, according to an appropriate fracture criterion, would propagate at an angle θ. Since P_o is insufficient to cause crack initiation (S_1 is less than the tensile strength of the material) or crack propagation (the stress intensity factors are less than the critical stress intensity factors of the material) a new value, P_1, must be obtained. This can be calculated directly for crack tip B and for principal stress S_1. The problem is that when P is increased to P_1, stress redistribution can take place so that the new maximum principal stress is at a different location and/or at a different orientation. Similarly, crack tip B may want to propagate at a different angle and, possibly, a different crack tip may have larger stress intensity factors than crack tip B. Consequently, the determination of the correct value of P involves sequential calculations of P_1 followed by a search for the maximum principal stress or the maximum stress intensity factors. It is, therefore, an iterative process. The procedure for calculating P_1 for crack initiation is as follows: the maximum principal stress S_1 is at an angle ϕ with respect to the cartesian coordinate system. The stress S_1 can be constructed from the sum of the stresses due to each load set:

$$S_1 = \sigma'_{xv} + \sigma'_{xc} \tag{1}$$

where v and c denote variable and constant stress, respectively. The superscript (prime) refers to rotated stresses, i.e.:

$$\sigma'_x = \sigma_x \cos^2\phi + 2\tau_{xy} \sin\phi \cos\phi + \sigma_y \sin^2\phi \ . \tag{2}$$

Since one wants S_1 to be equal to T (the tensile strength) for crack initiation at angle ϕ one has

$$T = \kappa\, \sigma'_{xv} + \sigma'_{xc} \tag{3}$$

where κ is a multiplicative factor. Hence

$$\kappa = \frac{T - \sigma'_{xc}}{\sigma'_{xv}} \ . \tag{4}$$

The variable load vector is factored up by κ and a complete stress analysis is done to determine if the point of initiation has changed or if the angle ϕ has changed. If so, a new κ must be calculated and another stress analysis performed. This is done until the angle and point of initiation do not change.

Of course, Figure 1 is a simplified example. In FEFFLAP the variable load is entirely general and includes, for example, pressure due to fluid flow in cracks and interfaces.

Minimum Aperture for Fluid Flow

FEFFLAP was tested against the results of a set of hydrostone block experiments [3]. It became evident during the analysis that one of the more important parameters in the experiments was the minimum crack aperture for fluid flow. That is, there is an aperture below which no fluid penetration will occur. This is quite important because the extent of fluid penetration strongly affects fracture instability as well as angle of propagation. This aperture depends on the surface tension of the fluid and the pressure in the fluid for the static case. The minimum aperture for flow in FEFFLAP is based on a value which is estimated from surface tension theory [4]. Essentially, the radius of curvature of the fluid front R (Figure 2) is proportional to the surface tension of the fluid and inversely proportional to the pressure in the fluid. Surface tension for the fracturing oil in the experiments was estimated from Reference [5]. At an oil pressure of 2000 psi the minimum opening for oil penetration is about 10^{-5} inches. This model gives a maximum possible wetted length that can be pressurized during each stage of the hydrofracture process.

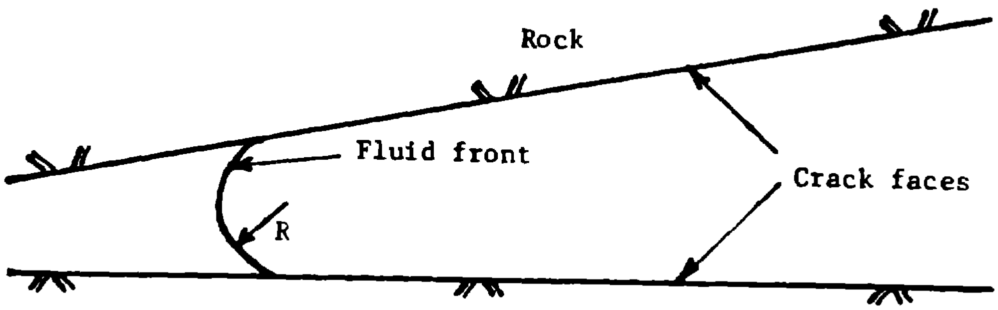

Figure 2. The Fluid Front Stops In a Narrowing Channel Due To Surface Tension.

VERIFICATION AND EXAMPLE PROBLEMS

Solutions to two problems are presented in this section to show the accuracy and versatility of FEFFLAP. In the first problem, the stress intensity factors for two radial cracks from a borehole, as calculated by FEFFLAP are compared to analytical values. In the second one, FEFFLAP calculations are correlated to results of physical experiments performed on jointed hydrostone blocks.

Pressurized Crack and Borehole

FEFFLAP was tested on the cracked borehole problem shown in Figure 3 by calculating Mode I stress intensity factors for two types of loading: a remote biaxial tensile stress, and uniformly pressurized borehole and cracks. The results were compared to established values [6] to obtain an estimate of FEFFLAP's accuracy. The mesh shown in Figure 3 represents quadrant 1 of the sketch and is all that is required to determine displacements and stresses. For both types of loading each crack length was 1.5 times the borehole radius. The Mode I stress intensity factor calculated in FEFFLAP was 7 percent higher than the established value for both cases. These results are quite good when one considers the coarse finite element mesh. In addition, the mesh is truncated at 10 times the borehole radius while the established values correspond to an infinite medium.

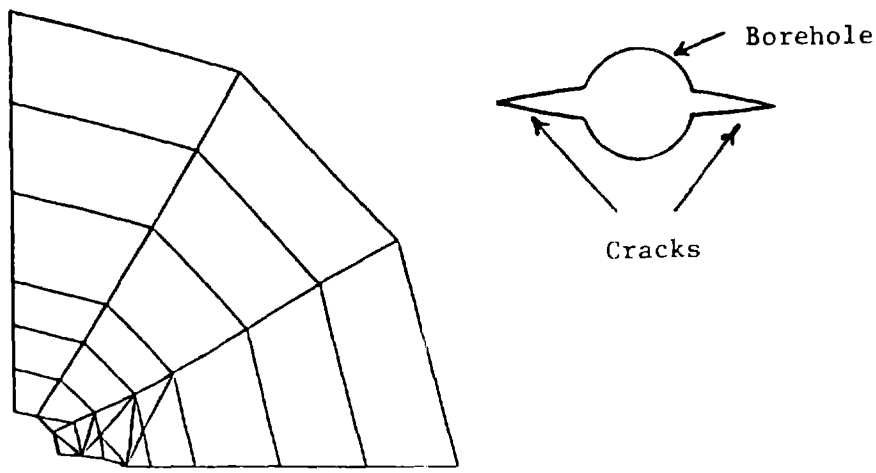

Figure 3: Four-fold Symmetry Finite Element Mesh for a Borehole with Two Opposite Radial Cracks. The Mesh has 28 Elements and 90 Nodes.

Hydrostone Block Experiments

Sixteen hydrostone block experiments were performed at LLNL to provide physical test data related to hydrofractures crossing interfaces [3]. The basic test layout is shown in Figure 4. The problem involved two types of hydrostone separated by an interface, and also included the steel platens that were used to load the block. Thus three different solid material types were used. Four joint-interface types were required: (1) the interface between the two hydrostone materials, (2) the interfaces between steel platens and the hydrostone, (3) the joint elements that are inserted into the crack as it propagates, and (4) a set of joint elements around the interior of the borehole, which provides a convenient way to pressurize the hole. The last two joint types are necessary for the fluid flow part of the analysis.

In order to determine the adequacy of FEFFLAP, a 2-D code, to handle the 3-D geometry of Figure 4, the stresses in the mid-vertical section of the block were calculated both with a plane stress FEFFLAP solution, and with a 3-D jointed block code. Results agreed to better than 1% [2].

Then, two of the tests were analyzed with FEFFLAP using the mesh shown in Figure 5. Figure 6 shows the results of a FEFFLAP analysis of one experiment in which the crack stopped at the interface. Vertical and horizontal loading stresses were 700 and 100 psi, respectively, and the peak pressure in the borehole was 2800 psi. In Figure 7 the FEFFLAP analysis of another experiment shows that a crack reinitiates from the interface. For this case the vertical and horizontal loads were 1800 and 750 psi respectively, and peak borehole pressure was 3400 psi.

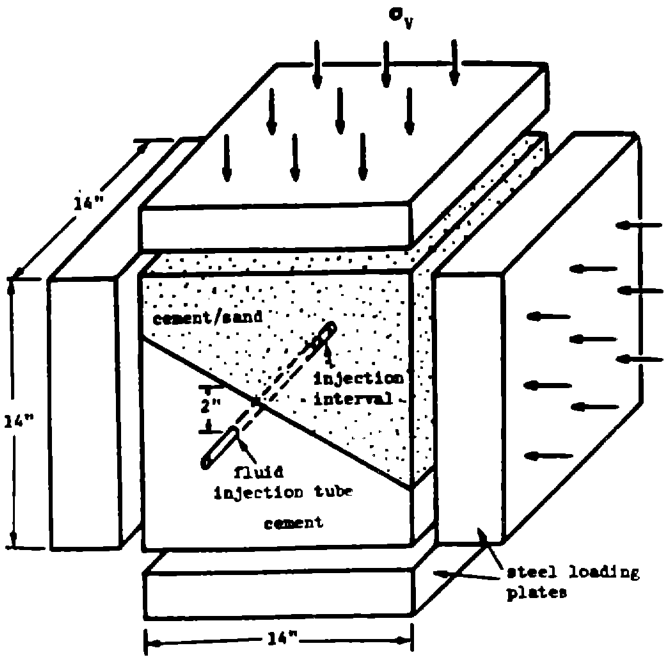

Figure 4: Physical Layout of Jointed Hydrostone Block Experiment (3).

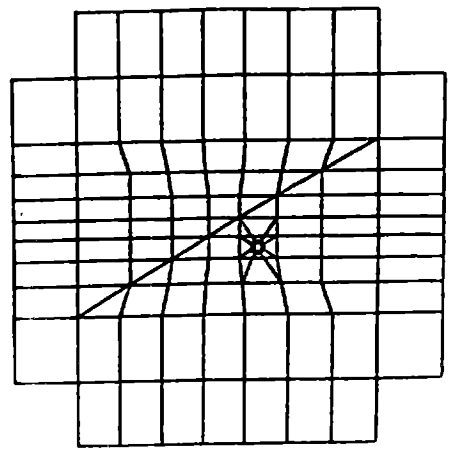

Figure 5: Mesh Used for FEFFLAP Analysis of the Block Tests; the Mesh has 122 solid Elements, 46 Joint Elements, and 492 Nodes.

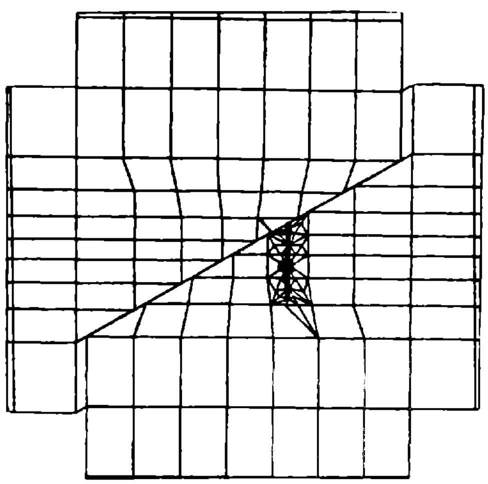

Figure 6: Crack Stops at Interface in Hydrostone Block Experiment and FEFFLAP Analysis.

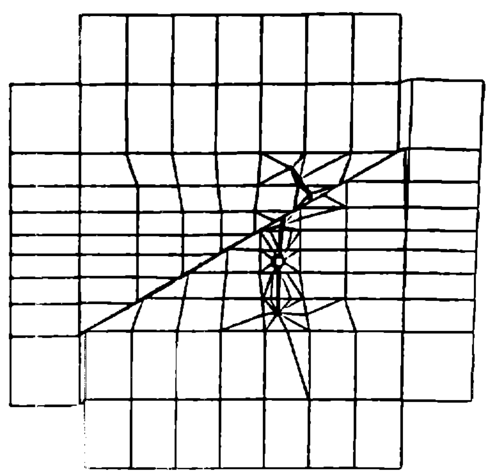

Figure 7: Crack Penetrates Interface in Hydrostone Block Experiment and FEFFLAP Analysis.

SUMMARY

We have developed a state-of-the-art model to describe fluid-driven fracture propagation in naturally jointed gas-bearing rock formations. It is a finite element code, named FEFFLAP (Finite Element Fracture and Flow Analysis Program). The program is highly interactive, with extensive graphical displays of the fracture behavior. Many automatic features for input generation, zoning, and rezoning make the code particularly efficient. The fracture mechanics, solid mechanics, and fluid mechanics are fully coupled. This paper relates some recent improvements made to the code. Also, model verification has been performed against analytical solutions and physical experiments.

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